PARTICLE SIZE CHARACTERISTICS OF SUSPENDED SEDIMENT IN HILLSLOPE RUNOFF AND STREAM FLOW

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ABSTRACT

This study examines the particle size characteristics of hillslope soils and fluvial suspended sediments in an agricultural catchment. Samples of surface runoff and stream flow were collected periodically and analysed for the size distributions of the effective (undispersed) sediment. This sediment was subsequently dispersed and the ultimate size distributions determined. The median effective particle size of stream suspended sediment was considerably coarser than the median ultimate particle size, indicating that most of the load included a substantial proportion of aggregates. Moreover, the proportion of fine material (i.e. silt and clay) increased, and the proportion of sand-sized material decreased, with increasing discharge. This decrease in sediment size with increased flow, which is contrary to the traditional assumption of a positive discharge/particle size relationship, is thought to reflect: (i) the influx of silt and clay, predominantly the former, originating on the catchment slopes and brought to the stream by overland flow along vehicle wheelings, roads and tracks; and (ii) erosion of fine material from the channel bed and banks. During large storms, however, the proportion of sand-sized sediment increased during the rising limb of the hydrograph, as a result of the entrainment of coarser source material from the valley floor during overbank flooding. The stream suspended sediment was finer than the catchment soils and considerably finer than material eroding from the catchment slopes during storms. The degree of clay and silt enrichment in the suspended sediments was largely the result of preferential deposition of the coarser fraction during the transport and delivery of sediment from its source to basin outlet. The data from this study confirm that a significant mode of sediment transport in fluvial systems is in the form of aggregates, and that the dispersed sediment size distribution is inappropriate for determining the transportability of sediment by flow. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Past research on erosion within river basins has tended to focus on the total amounts of material eroded from hillslopes (i.e. gross erosion rates), and on the efflux of suspended sediment from the basin as a whole (i.e. net sediment yield). Recent work, however, has directed attention more explicitly to the properties of the eroded material and their relationship to those of the source material. This has been stimulated, in part, by an increased awareness of the importance of sediment-associated transport in non-point pollution and the movement of contaminants through terrestrial and aquatic ecosystems. Sediment is a major transport medium for nutrients, such as nitrogen and phosphorus, and contaminants, such as trace metals, pesticides and herbicides (Juracic *et al*., 1986; Novotny and Chesters, 1989). The particle size characteristics of mineral sediment is of particular importance in this regard, because many of these substances are bound to clay particles. The selective mobilization of fine sediment (and sediment-associated nutrients) during erosion, therefore, causes enrichment in nutrients and contaminants, and may concentrate these substances by several orders of magnitude above ambient water concentrations (Ongley, 1982). A knowledge of the processes involved in the generation, transport and deposition of such sediment, and of the associated changes in the particle size characteristics of sediment during erosion, is clearly of fundamental importance to an understanding of the fate of such chemicals.

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Improved knowledge of the particle size characteristics of eroded sediment has also been seen as a basis for a better understanding of fluvial transport dynamics and the development of improved transport relationships (Walling, 1988; Sutherland and Bryan, 1989). However, whilst particle size data are frequently available for soils and sediments, these are almost always analysed in the laboratory after the sediment is fully dispersed into its primary particles. Such data are termed ‘ultimate’ particle size data, since they refer to the individual particles making up the sediment. Yet there is increasing evidence to indicate that most of the sediment moving through a drainage basin, particularly agricultural basins, will be transported as aggregates rather than as discrete separate grains. Thus, the size distribution of transported sediment in the field, often termed the ‘effective’ particle size distribution (after Ongley *et al*., 1981), may be quite different from the size distribution of the primary particles (sand, silt and clay) that result when the eroded sediment is dispersed. It is therefore crucial to consider the effective particle size of sediment, because this will govern the actual behaviour of the transported sediment. Moreover, the pollution potential of eroded sediment will be greater if clays are transported as individual particles, rather than as larger aggregates.

Very few data are available on the size distribution of sediment in the form that it is eroded in the field. Work carried out by scientists at the United States Department of Agriculture (USDA) (e.g. Young, 1980; Meyer *et al*., 1980; Alberts *et al*., 1983; Foster *et al*., 1985; Meyer *et al*., 1992) has provided some important information on the size characteristics of eroded sediment from agricultural soils in the United States, although much of this research was conducted on small experimental plots under simulated rainfall. There are virtually no data on the characteristics of sediment eroded under natural conditions and there has been no examination of these characteristics over entire hillslopes. A notable exception is the work of Parsons *et al*. (1991) in southern Arizona, although in that study, sediment was still dispersed in the laboratory because the sandy catchment soils were not well aggregated and tended to erode mostly as primary particles. There have also been few attempts to assess the grain size composition of the sediment moving through the delivery system of entire drainage basins, despite recognition that such data may provide the information needed to understand the transfer processes better (Walling, 1990). Sutherland and Bryan (1989) have published results on the variability of particle size characteristics of sheetwash sediments and fluvial suspended sediments for the small semiarid Katiorin basin in Kenya, but again, samples were dispersed in the laboratory prior to analysis. Whilst this may be appropriate for non-aggregated sandy material, as was the case for the Katiorin sediments, most of the sediment eroded from agricultural soil, as noted above, is composed of aggregated particles. Dispersing such sediment in the laboratory would clearly be inappropriate in terms of developing an improved understanding of the erosion dynamics and transport processes involved in sediment delivery.

The present investigation was undertaken against this background. The main objective of the study was to provide detailed information on the size characteristics of sediment in the form that it is eroded and transported in the field under natural conditions, both across slopes and within streams. The study was conducted in a small agricultural drainage basin in north Oxfordshire, U.K., between August 1992 and July 1993, and formed part of a much broader investigation into the sediment delivery dynamics of the basin (see Slattery, 1994). The results are discussed in three sections. First, the particle size characteristics of stream suspended sediment are examined, with particular emphasis on intra-storm variations in sediment size distribution. Second, the size characteristics of sediment eroded from the catchment slopes are presented. (As these data have been discussed in detail elsewhere (Slattery and Burt, 1995), we limit ourselves here to presentation of summary information.) Finally, the relationship between slope and channel sediment is examined.

RESEARCH DESIGN

Study site

The study catchment (U.K. grid reference SP 356 362) is situated in the Cotswold hills, approximately 8 km northeast of Chipping Norton (Figure 1). The catchment has a drainage area of $6{\cdot}2\,km^2$ and its altitude ranges from 126 m at its outlet to 202 m on the northern divide. Slopes are gentle (around 1°) near the interfluves but steeper (>5°) in the central part of the basin. The stream network is moderately incised into the valley floors, and bank heights are commonly less than 1 m. Two major soil types have been identified within the basin (Jarvis *et*

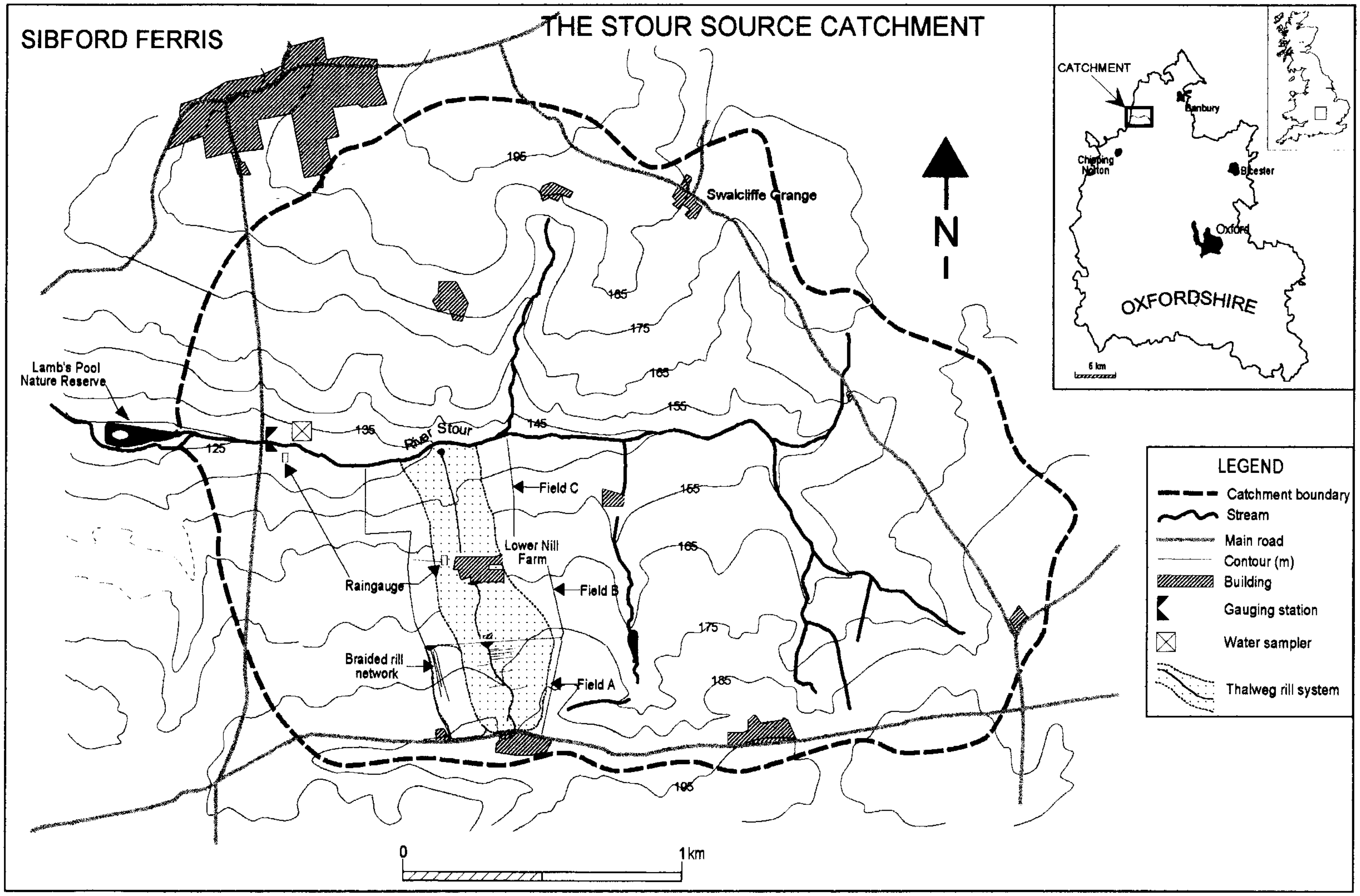

Figure 1. Map of the study catchment showing field instrumentation and location of the thalweg rill system (see text for explanation)

al., 1984). Brown calcareous earths of the Aberford series occupy the central portion of the basin; these are moderately stony, well-drained fine loamy soils. Ferritic brown earths of the Banbury series occur as bands across the northern and southern sections of the basin; these are stony, well-drained fine loamy soils. Both soils overlie Jurassic sediments: Northampton Sand and Great Oolite Limestone, respectively. Land use is mixed arable farming with extensive autumn sowing of wheat and barley.

Data collection and analysis

A gauging station was established at the catchment outlet in July 1992. A 90° V-notch weir with an Ott stage recorder was installed to provide continuous measurements of stream discharge. Two raingauges were also installed in the field: a tipping-bucket gauge at the catchment outlet (this was linked to a Campbell data logger and provided the time of each 0·2 mm of rainfall), and a Casella autographic natural siphon gauge near Lower Nill Farm (see Figure 1). A Rock and Taylor automatic pump water sampler was also installed just upstream from the gauging station. Water and suspended sediment samples were obtained from the stream every 4–6 h during low flows and every 15 min during storm events.

Catchment slopes were monitored for surface runoff and erosion between August 1992 and July 1993. Slope runoff was generally of two types: (i) concentrated overland flow along vehicle wheel tracks (wheelings), and (ii) flow in rills. Concentrated flow along wheelings was observed frequently during the very wet months of December 1992 and January 1993. These flows were generally thin (less than 1 cm depth) and transported only small amounts of sediment down slopes. However, three fields along the southern slopes of the basin produced considerable amounts of surface runoff during the winter storms (see Figure 1). Along the western boundary of Field A, closest to the basin divide, downslope wheelings generated runoff on several occasions, eventually eroding the soil to produce a braided rill network. In the centre of Field A, an extensive thalweg rill system developed. Here, the rill network consisted of a single channel developed along the valley floor which was supplied with runoff and sediment by a series of ‘feeder rills’ developed along wheelings on the steeper valley-side slopes. This rill system extended into the adjacent field downslope (i.e. Field B, Figure 1), although here the network contained only a single channel in the valley floor. During a storm on 13 January 1993, flow from the rill system reached Field C, concentrating along a wheeling to form a single channel with a fan deposit directly adjacent to the stream. Thus, the entire rill system, once fully developed, formed a continuous and efficient link for the delivery of water and sediment between the upper fields and the valley floor (see Slattery *et al*. (1994) for a detailed discussion on the dynamics of the thalweg rill system). Runoff was sampled at several locations along the thalweg rill, as well as at other locations in the basin. For rill flow, samples were collected by hand by simply placing 0·5 litre plastic bottles into the flow. Concentrated runoff along wheelings was sampled by routing flow across portable hillslope flumes, constructed according to the design of Parsons and Abrahams (1989).

The hillslope and stream suspended sediment samples were returned to the laboratory immediately following each storm event and were first analysed for the size distributions of the effective (i.e. undispersed) sediment. Each sample was wet-sieved through a nest of sieves, with 2000, 1000, 500, 250, 125 and 63 μm openings, to determine the content of sand-sized sediment. Wet-seiving consisted of gentle, thorough sieve-by-sieve washing of sediment, using ample clean water to flood each sieve. The material passing through the 63 μm sieve (i.e. the silt/clay fraction) was then transferred to a large beaker. Five subsamples were taken from the silt/clay fraction by pipette and run through a Cilas 920 laser granulometer to determine the mean, undispersed sediment sizes at 31, 16, 8, 4 and 2 μm. The remaining sediment in the beaker was then dried at 50°C and weighed,

After determining the effective grain size distributions, the sediment from each hillslope sample was combined into one of three sediment-size groups: (a) coarser than 250 μm; (b) 63–250 μm; and (c) finer than 63 μm. The sediment in each of these large, medium and fine size groups was subsequently dispersed (1·0 per cent sodium hexametaphosphate) and then sieved and run through the laser granulometer to obtain the primary particle content of each group. For stream suspended sediment, however, samples were generally too small for grouping into the three aggregate size classes. Stream samples were therefore dispersed immediately following determination of the effective size distribution, and the ultimate grain size distribution measured using the techniques described above. It should be noted that all particle size analysis was conducted prior to removal of organic material from the samples, as this would have destroyed any aggregates present in the sediment.

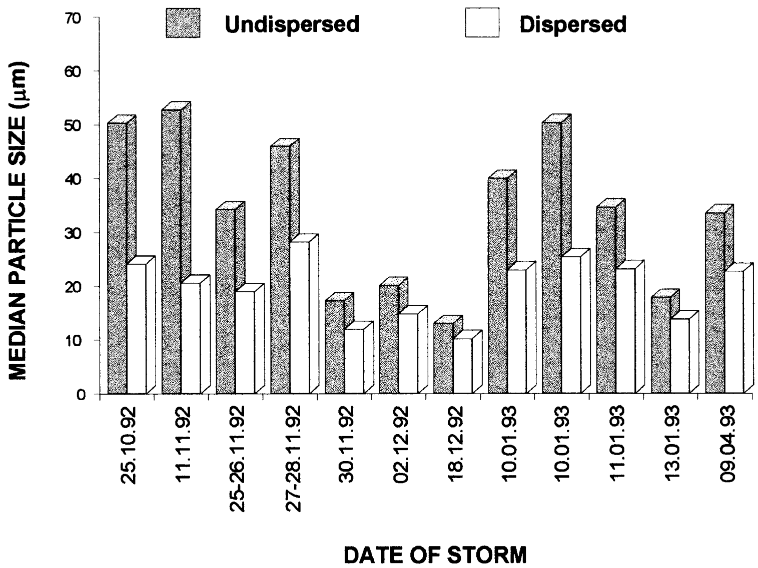

Figure 2. Comparison of ultimate (dispersed) and effective (undispersed) median particle size of suspended sediment at peak discharge for 11 storms. Note that two sets of data for the 10 January 1993 storm are included, as sediment was sampled exactly 3 h either side of peak discharge

SIZE CHARACTERISTICS OF STREAM SUSPENDED SEDIMENT

General characteristics

Figure 2 shows the median effective (undispersed) and ultimate (dispersed) particle size of stream suspended sediment at peak discharge for 11 storms during the study period. The median effective particle size is in all cases considerably coarser than the median ultimate particle size, indicating that much of the suspended sediment in the stream included a substantial proportion of aggregates. Figure 3 presents plots of the relationships between the effective and ultimate particle size composition of suspended sediment (percentage clay and sand) and water discharge for all stream samples. Discharge appears to exert a significant influence on both the effective and ultimate particle size distribution, with the proportion of fine material (i.e. silt and clay as a percentage of the total) increasing, and the proportion of sand-sized particles decreasing, with increasing discharge. Low flows transport a greater percentage of aggregated sand-sized sediment; at high discharge, the proportion of undispersed to dispersed sand-sized sediment is similar. This suggests that, while the suspended sediment load generally becomes finer as discharge increases, the sediment also becomes less well aggregated, probably due to increased turbulence and hence greater aggregate breakdown, at higher flow. Throughout most of the discharge range, most of the clay seems to move as primary particles or at least clay-sized aggregates. It should be noted that the data were also analysed in absolute terms (i.e. on a per weight basis) and gave almost identical results to the relative concentration data in Figure 3.

The general trend in the particle size/discharge relationship shown in Figure 3 is contrary to the traditional assumption that increased flow facilitates the transport of larger particles and that a positive relationship exists between discharge and the magnitude of the coarse fraction (Horowitz, 1985). Reid and Frostick (1994), however, suggest that there is a varied relationship between suspended sediment size and flow, and remind us that situations where particle size remains essentially constant, increases or decreases with increasing discharge have all been described in the literature (Walling and Moorehead, 1987, 1989). The principal reason for this variability in the sediment size/discharge relationship is, of course, that the suspended load is affected not only by the hydraulic conditions within the channel but also by the dynamics of erosion and sediment delivery processes operating throughout the entire basin. The potential influence of sediment delivery and conveyance

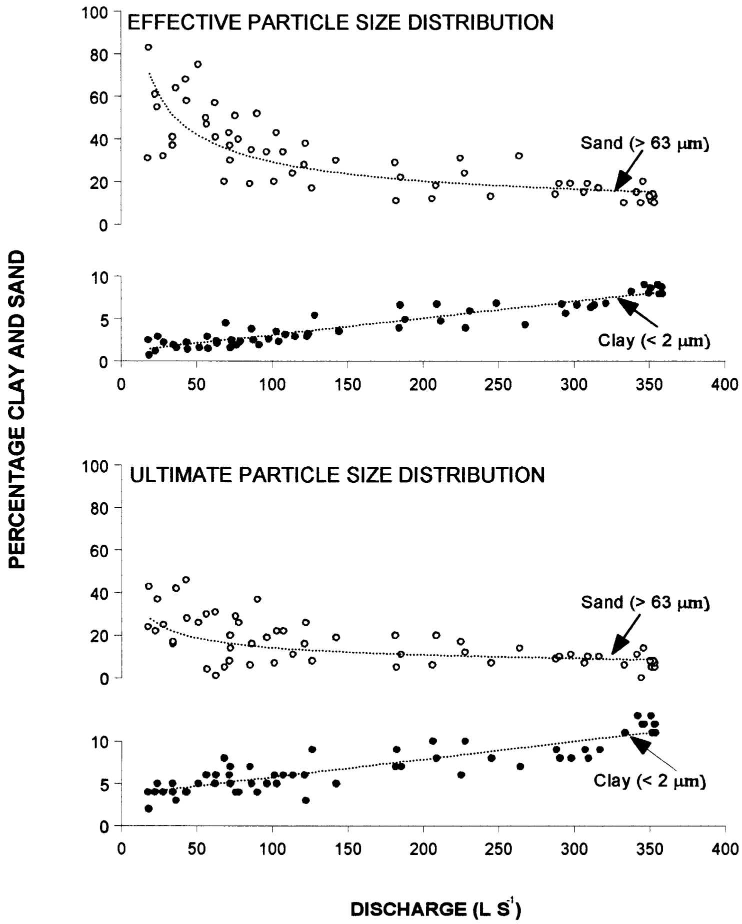

Figure 3. Relationships between the clay and sand content (effective and ultimate) of suspended sediment and discharge for all storms

processes in controlling the particle size characteristics of stream suspended sediment is illustrated further by examining three storms in detail.

Intra-storm variation of particle size characteristics

Figure 4 shows temporal variations in the particle size characteristics of suspended sediment during three storm events. These storms are characteristic of cyclonic rainfall that occurs throughout central England during the winter period and are representative of the range of responses observed in the particle size/flow relationship during the study period.

The effective particle size distribution of the suspended sediment immediately preceding the storm of 25 November 1992 (i.e. sample a, Figure 4a) is characterized by a substantial proportion of sand-sized material: 48 per cent of the sediment is transported as medium and large aggregates (i.e. >63 μm), whereas the ultimate size distribution indicates that only 28 per cent of the sediment actually consists of primary sand. These data indicate that much of the primary silt and clay (mainly the former) is incorporated within medium and large aggregates. Observations made in the field during sampling revealed that most of the coarse suspended sediment transported in pre-storm baseflow is remobilized sediment deposited along the channel bed during the previous storm event. The sediment record then shows an increase in the proportion of silt- and clay-sized material, and a decrease in the proportion of sand-sized material, with increasing discharge. During the recession limb, the proportion of sand-sized sediment increases at the expense of both silt- and clay-sized material. This pattern, which reflects the general trend of decreasing sand and increasing silt and clay with increasing discharge

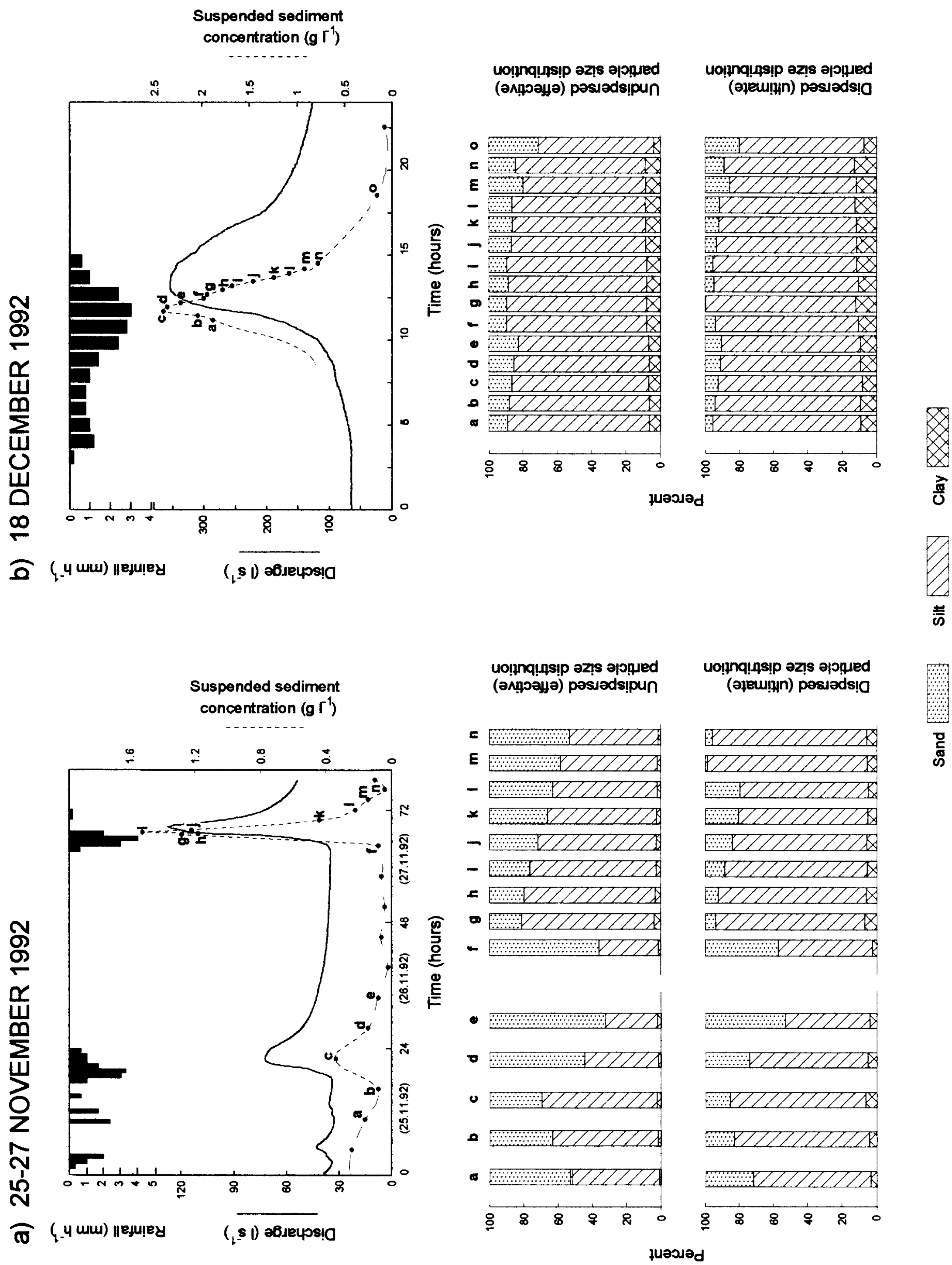

Figure 4. Changes in effective and ultimate particle size distribution in suspended sediment in response to discharge during three storms: (a) 25 and 27 November 1992; (b) 18 December 1992

(Figure 3), cannot be related to hydraulic conditions in the channel, that is, increased turbulence or shear velocities occurring at higher flow. In this case, the decrease in sediment size with increased flow is thought to

reflect: (i) the influx of silt and clay, predominantly the former, originating on the catchment slopes and brought to the stream by overland flow along vehicle wheelings, roads and tracks; and (ii) erosion of fine material from the bed and banks of the channel.

The storm on 27 November 1992 shows the same pattern in the particle size composition/discharge relationship, but there is a much better level of detail in the suspended sediment record (Figure 4a). The effective particle size distribution of the suspended sediment immediately preceding the storm (sample f) is very similar to that sampled on the recession limb of the 25 November 1992 hydrograph (sample e); almost 64 per cent of the sediment on 27 November is transported as sand-sized aggregates (67·6 per cent on 25 November), whilst the ultimate size distribution indicates that only 42·3 per cent of the sediment actually consists of primary sand (46·4 per cent on 25 November). The effective size distribution then shows very clearly the trend of increasing sand and decreasing silt and clay with decreasing discharge; this effect begins towards the end of the rising limb and continues throughout the recession. This storm also shows clear positive hysteresis in the relationship between particle size composition and discharge, with the suspended sediment in sample g on the rising limb being almost 0·5ϕ unit finer than that in sample k on the recession limb, which is essentially the same discharge. This again seems to result both from flushing of fine material during the early part of the storm and from increased aggregate breakdown, as discussed previously.

The storm on 18 December 1992 (Figure 4b) also provides a detailed picture of the variation of particle size with discharge but shows a more complex response than those discussed above. Two trends are of note in the particle size record. The first is that the proportion of sand-sized sediment *increases* during the rising limb of the hydrograph, from an initial value of 11 per cent (sample a) to 17 per cent (sample e), but then decreases to a fairly constant value (*c*. 10·5 per cent) during the peak in discharge (samples f to i). The proportion of sand-sized sediment then increases again (i.e. from sample j onwards), but here in response to *decreasing* discharge on the recession limb. The sample taken at 18:30 (sample o) shows that 28·6 per cent of the suspended sediment is effectively sand-sized. The second trend in the data is that clay content, both in its effective and ultimate forms, increases throughout the storm and only shows a decrease in sample o at 18:30. The initial trend of increasing sand and decreasing silt content with increasing discharge cannot be accounted for in terms of increasing transport capacity within the channel. Although such reasoning is physically sound, it would contradict the earlier findings which showed that the proportion of sand-sized sediment generally decreases with increasing discharge. This initial trend can therefore only be explained in terms of the sediment delivery processes and sediment sources operating within the basin. Observations made in the field during the event revealed that the stream burst its banks at a discharge of *c*. $200 \mathrm{l\,s^{-1}}$, flooded the valley floor and caused significant erosion of cultivated topsoil near the channel. It is suggested that inundation of the valley floor during the early part of the storm resulted in the entrainment of a relatively greater proportion of coarser source material, thereby producing a positive relationship between the proportion of coarse sediment and stream discharge. The valley floor is an area with low slope angles which would reduce the efficiency of sediment delivery from the catchment hillslopes (cf. Walling and Moorehead, 1987, 1989); this in turn would result in the deposition of coarse particles which only become remobilized and transported by overbank flow during floodplain inundation. The proportion of sand-sized material in the suspended sediment decreases during peak discharge once the floodplain is depleted of this coarser sediment. The results of sediment source ‘fingerprinting’ using mineral magnetic measurements (see Slattery *et al*., 1995) confirmed that the majority of the suspended sediment transported during peak discharge was cultivated topsoil originating from the valley floor. The increase in clay content throughout the storm can be ascribed to: (i) the entrainment of fine particles in the floodplain by overbank flow, particularly organic material, not previously affected by surface runoff; and/or (ii) the delivery of fines directly to the stream channel by surface runoff along roads and wheelings.

Inter-storm variation of particle size characteristics

The preceding discussion has shown that the particle size characteristics of stream-suspended sediment exhibit appreciable temporal variation within individual storms. Such variability has been attributed to temporal variations in the nature and efficiency of the sediment delivery processes operating during storms, the importance of particular sediment sources, and the operation of in-stream processes. Evidence of inter-storm

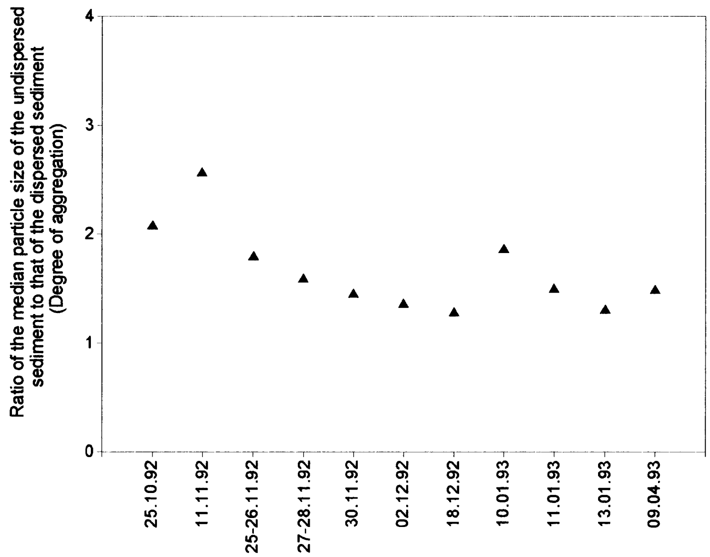

Figure 5. Temporal variation in the degree of aggregation in suspended sediment

contrasts in particle size distributions is afforded by Figure 2. The data indicate that the suspended sediment load became finer with time from the storm on 25 October 1992 (median effective size = 50·29µm) to that on 18 December 1992 (median effective size = 13·09µm). The progressive breakdown and flushing of coarser aggregates from the bed of the channel, the incorporation of finer material at higher discharges, and continued wetting and drying of the soil surface would all appear to have contributed to this fining trend. Suspended sediment was noticeably coarser during the storms of 10 and 11 January 1993. This coarsening appeared to be related to extensive needle-ice activity following a two-week freeze in late December, which disrupted the soil surface making sediment available for subsequent entrainment. Data on the temporal change in soil surface properties in the catchment, documented in Slattery (1994), showed that relatively rapid freezing and thawing caused the breakdown of larger clods into smaller ones, which subsequently became remobilized and transported by the flow. The sediment load is then finer during the 13 January 1993 storm (although still coarser than during the 18 December 1992 storm) owing to increased aggregate breakdown, but becomes significantly coarser during the 9 April 1993 storm, most probably owing to a build-up of coarser sediment on the channel bed between the two events. In terms of sediment supply, therefore, freezing seems to have 'reset' the system, making coarser aggregates available for entrainment.

In addition to the temporal variation in particle size characteristics between storms, there is an apparent inter-storm variation in the degree of aggregation. Figure 5 shows the change in the degree of aggregation (expressed here as the ratio of the median particle size of the undispersed sediment to that of the dispersed sediment) in suspended sediment with time. The degree of aggregation shows an initial increase between 25 October and 11 November 1992 but then declines steadily to a minimum value during the 18 December 1992 storm. The fact that the degree of aggregation of the suspended sediment declines with time is most likely due to turbulent mixing associated with increased levels of discharge during the larger winter storms, which is sufficient to cause the break-up of the soil aggregates. It is also likely that the stability of eroded aggregates would decrease in water during transport through the basin sediment system. The degree of aggregation increases after the period of ground frost (i.e. on 10 January 1993), owing to the availability of relatively coarser sediment, but begins to decrease again most probably in response to turbulent mixing during increased discharge. The data from the 9 April 1993 storm show a slight increase in the degree of aggregation due to the gradual build-up of coarser material during February and March.

Table I. Size distributions of dispersed surface soil, sediment as eroded in runoff, and this sediment after dispersal. Note that the samples are identified as follows: the first number indicates the sample number; the second number identifies the date of sampling (18 for the storm of 18 December 1992 and 13 for the storm of 13 January 1993

		Sample 1·18*		Sample 2·8†		Sample 3·13‡		Sample 4·13§		Sample 5·13¶		Sample 6·13**	
Particle size class (μm)	Dispersed soil	Eroded sediment	Dispersed sediment	Eroded sediment	Dispersed sediment	Eroded sediment	Dispersed sediment	Eroded sediment	Dispersed sediment	Eroded sediment	Dispersed sediment	Eroded sediment	Dispersed sediment
1000–2000	0·3	0·0	0·0	0·5	0·0	2·4	0·1	2·5	0·2	2·1	0·0	2·3	0·0
500–1000	0·7	0·8	0·0	1·1	0·3	3·1	0·4	4·5	0·8	4·4	0·2	7·0	1·2
250–500	2·6	1·6	0·0	6·1	2·0	5·9	1·8	8·6	4·0	8·6	1·9	12·8	2·9
125–250	14·9	5·8	1·6	24·9	18·9	29·0	25·7	39·5	33·7	33·3	24·5	15·7	8·1
63–125	19·1	7·0	2·3	5·9	7·5	10·1	9·1	9·7	12·5	13·4	13·9	15·7	9·3
31–63	12·8	14·8	10·5	9·3	8·5	12·4	11·4	7·8	6·5	9·1	6·7	16·4	21·7
16–31	13·8	18·9	19·4	12·2	13·0	12·3	15·2	8·5	11·7	8·3	14·4	9·9	16·3
8–16	12·7	21·5	23·7	15·6	16·6	10·3	14·7	7·9	11·5	8·1	14·5	8·0	15·5
4–8	10·5	15·4	21·2	12·4	15·9	7·2	10·9	5·6	9·4	6·3	12·1	5·9	12·3
2–4	6·7	8·0	12·2	6·7	9·9	4·1	6·1	3·0	5·5	3·7	7·0	3·5	7·2
<2	5·9	6·3	9·0	5·2	7·3	3·2	4·7	2·4	4·2	2·7	4·9	2·9	5·4

* Sample taken from small rill on Field A (Figure 1) on 18 December 1992; mean rill discharge=1·1 l s^{-1}, mean flow velocity=0·35 m s^{-1}, mean sediment concentration=6·5 g l^{-1}
† Sample taken from large rill on Field A (Figure 1) on 18 December 1992; mean rill discharge=6·2 l s^{-1}, mean flow velocity=0·74 m s^{-1}, mean sediment concentration=10·5 g l^{-1}
‡ Sample taken from large rill on Field A (Figure 1) on 13 January 1993; mean rill discharge=11·2 l s^{-1}, mean flow velocity=1·13 m s^{-1}, mean sediment concentration-16·8 g l^{-1}
§ Sample taken from thawleg rill on Field A (Figure 1) on 13 January 1993; mean rill discharge=31·1 l s^{-1}, mean flow velocity=1·24 m s^{-1}, mean sediment concentration=27·5 g l^{-1}
¶ Sample taken from feeder rill on Field A (Figure 1) on 13 January 1993; mean rill discharge=2·5 l s^{-1}, mean flow velocity=0·45 m s^{-1}, mean sediment concentration=13·7 g l^{-1}
** Sample taken from rill adjacent to stream on Field C (Figure 1) on 13 January 1993; mean rill discharge=2·4 l s^{-1}, mean flow velocity=0·40 m s^{-1}, mean sediment concentration=3·4 g l^{-1}

SIZE CHARACTERISTICS OF HILLSLOPE SEDIMENTS

The size distributions of sediment eroded from the catchment slopes in surface runoff and rill flow, as indicated by granulometric analysis, are summarized in Table I. As these data have been discussed in detail elsewhere (Slattery and Burt, 1995), we present only summary information in this section.

The effective size distribution of eroded (i.e. undispersed) sediment was, in all cases, much coarser than the (ultimate) size distribution of the same sediment when dispersed, indicating that much of the sediment in hillslope runoff eroded as aggregates. Most of the clay eroded as primary clay, with only small percentages incorporated in the aggregates. For sample 1.18, the size distribution of both the eroded and dispersed sediment was significantly finer than that of the matrix soil, with considerable enrichment evident in both the silt and clay fractions. Enrichment ratios (ER) were determined from the following equation:

$$ER = \frac{\text{\% sediment in a given size class in surface runoff}}{\text{\% sediment in a given size class in matrix soil}} \tag{1}$$

ER values greater than 1·0 represent enrichment: a given size class forms a greater proportion of the transported load in runoff than in the matrix soil. ER values less than 1·0 represent depletion: a given size class forms a greater proportion in the matrix soil than in the transported load. The size distribution of the matrix soil was determined from 20 samples taken from throughout the catchment. For the dispersed sediment in sample 1.18, enrichment ratios were 1·5 for both the clay and silt fractions, and 0·10 for sand. Computing enrichment ratios for the eroded sediment is, however, problematic as the matrix soil is itself defined by the dispersed particle size distribution, which would clearly be quite different to the soil's effective particle size distribution. Despite several attempts in the soil science literature, obtaining an effective size distribution for a soil remains extremely difficult, particularly when the soil surface is crusted, as is the case here. Even though data for what is essentially the ped size distribution of the field soils are not available, the fact that there was more clay and silt in the sediment than in the matrix soil does suggest that the flow in the rill channel at the time of sampling was only competent enough to transport the finer silt and clay fraction of the sediment, at the expense of the coarser sand fraction. The low discharge and velocity data given in Table I support this interpretation of the selective or preferential erosion of fines.

All samples from the 13 January 1993 storm (i.e. samples 3.13–6.13) were characterized by size distributions which were considerably coarser than that of the dispersed matrix soil, with more medium and large aggregates being transported in the runoff. This appearted to be directly related to the flow conditions in runoff and rills, which were more efficient in transporting this coarser material. The data from the main rill channel (sample 4.13), for example, show that 16 per cent of the sediment was transported as large aggregates, despite the fact

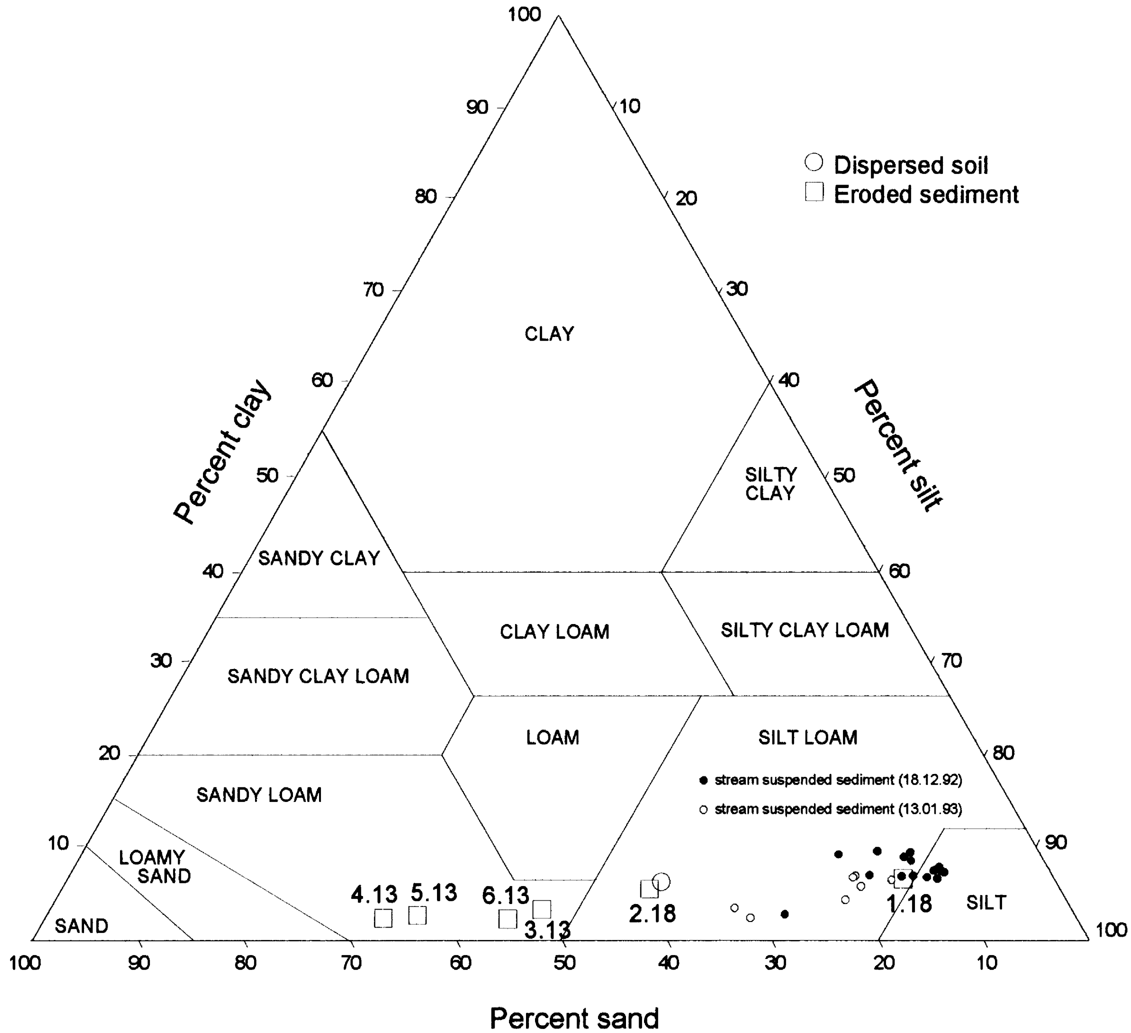

Figure 6. Differences between the texture of the dispersed (ultimate) surface soil and the 'texture' of the resulting undispersed sediment as it erodes in surface runoff during the 18 December 1992 and 13 January 1993 rainstorms. The particle size compositions of the undispersed suspended sediment in the stream during the two storms are also plotted on the diagram. The size distribution of the dispersed (matrix) soil represents a mean of 20 surficial (0–5 cm) samples taken throughout the catchment prior to the two storms

that only 5 per cent of the primary sand was coarser than 250 µm. Also evident in these larger flows is the depletion of clay and silt relative to the dispersed matrix soil, with depletion ratios of 0·7 for both clay and silt. The fact that more aggregated material is being transported in the main rill channel, and that clay and silt have undergone depletion, can again be related to flow conditions. Mean discharge in the main rill was calculated at 31·11 s^{-1} and mean velocities 1·24 m s^{-1} (although velocities did fluctuate markedly along the main rill, with rates of greater than 2 m s^{-1} measured at several locations). Flow in the thalweg rill was thus fully competent at all times to transport the coarser material at the expense of the silt and clay fractions.

The slope sediment data presented in Table I are summarized in Figure 6. The size distribution of the dispersed matrix soil and the size distributions of the eroded hillslope sediments have been plotted on an USDA Textural Classification Chart. Summarizing, for sample 1.18, rill flow was unable to transport the coarser fraction of the sediment available in the matrix soil, and hence there is selective removal of fine particles at the expense of the coarse ones. Texturally, the sediment erodes as a very fine silt loam. The eroded sediment size

distribution of sample 2.18 is similar to that of the dispersed soil, indicating that the sediment eroding from the slopes is representative of the surface soil from which it was eroded, and that little selectivity or enrichment resulted under these conditions. Samples from the 13 January 1993 storm (samples 3.13–6.13), however, produced sediment that resembled sandy loams texturally, with each sample's sediment size distribution closely related to flow characteristics. In all cases, flow was fully competent to transport the coarse material. In essence, flow in these rills selectively removed the coarser particles as aggregates at the expense of the finer fractions. Thus, the term 'selective erosion' can refer to the preferential entrainment of both fine and coarse particles, depending on flow conditions.

RELATIONSHIP BETWEEN THE PARTICLE SIZE OF HILLSLOPE SEDIMENTS AND FLUVIAL SUSPENDED SEDIMENTS

One of the least understood components of the basin sediment system is the link between on-site erosion, soil loss from hillslopes and sediment yield at the basin outlet. The data presented in this paper, in adding to the limited information available on the size characteristics of sediment as it erodes in the field under natural conditions, also allows this linkage between the field and the river to be further elucidated.

The effective particle size distribution of the stream suspended sediment sampled during the 18 December 1992 and 13 January 1993 storms has been included on the textural diagram in Figure 6. Plotting the data in this way provides an effective visual comparison between the slope and stream data. The stream suspended sediment transported in both storms is considerably finer than both the catchment soil and the material eroding from the catchment slopes except for the sediment in sample 1.18, when hydraulic measurements conducted in the rill suggested that flow was only competent to transport the finer silt and clay fraction at the expense of the coarser sand fraction, thereby providing evidence of selective entrainment in the rill. Whilst it is often difficult to distinguish between the effects of preferential deposition and selective erosion, the data presented here suggest that the fineness of the suspended load for the 18 December 1992 storm was due, at least in part, to the selective erosion of fines in shallow rill flow. However, it still seems likely that the majority of fine enrichment seen in the suspended sediment is due to the preferential deposition or loss of coarse sediment during delivery, in the present case as a result of deposition at field boundaries and on the floodplain.

The data from the 13 January 1993 storm provided clearer evidence of preferential deposition as runoff was sampled in several rills as well as along vehicle wheelings. For this storm, sediments transported from the hillslopes were, on average, $1{\cdot}5\phi$ units coarser than the suspended sediment in the stream. For these data, enrichment ratios were determined from:

$$\mathrm{ER} = \frac{\%\text{ sediment in a given size class in channel runoff}}{\%\text{ sediment in a given size class in hillslope runoff}} \tag{2}$$

and are plotted in Figure 7. The effect of aggregation on enrichment is clearly evident, with the undispersed clay- and silt-sized sediment showing greater enrichment than the dispersed sediment.

The preceding analysis has shown that most of the material moving through the drainage basin was transported as aggregates rather than as discrete particles. One aspect yet to be addressed here is whether the aggregation evident in the stream sediment was the result of secondary aggregation processes occurring in the stream itself, or the survival of primary soil aggregates created in soil horizons. A review of current literature indicates that this aspect of sediment transport is under-researched and poorly understood. In the present study, scanning electron microscopy provided some evidence to indicate that most of the aggregation evident in the stream reflects the persistence of soil-derived aggregates during transport. Figure 8 shows a single, sand-sized aggregate sampled during the 9 April 1993 storm. This aggregate, typical of those sampled during storm flow, shows a complex structure and consists mainly of quartz silt and well formed kaolinite platelets with some illite and montmorillonite present. Organic matter is also incorporated within the aggregate and there is some evidence to suggest binding due to the secretion of sticky mucal substances. The occurrence of root holes formed *in situ* provides the strongest evidence for this being a soil-derived aggregate.

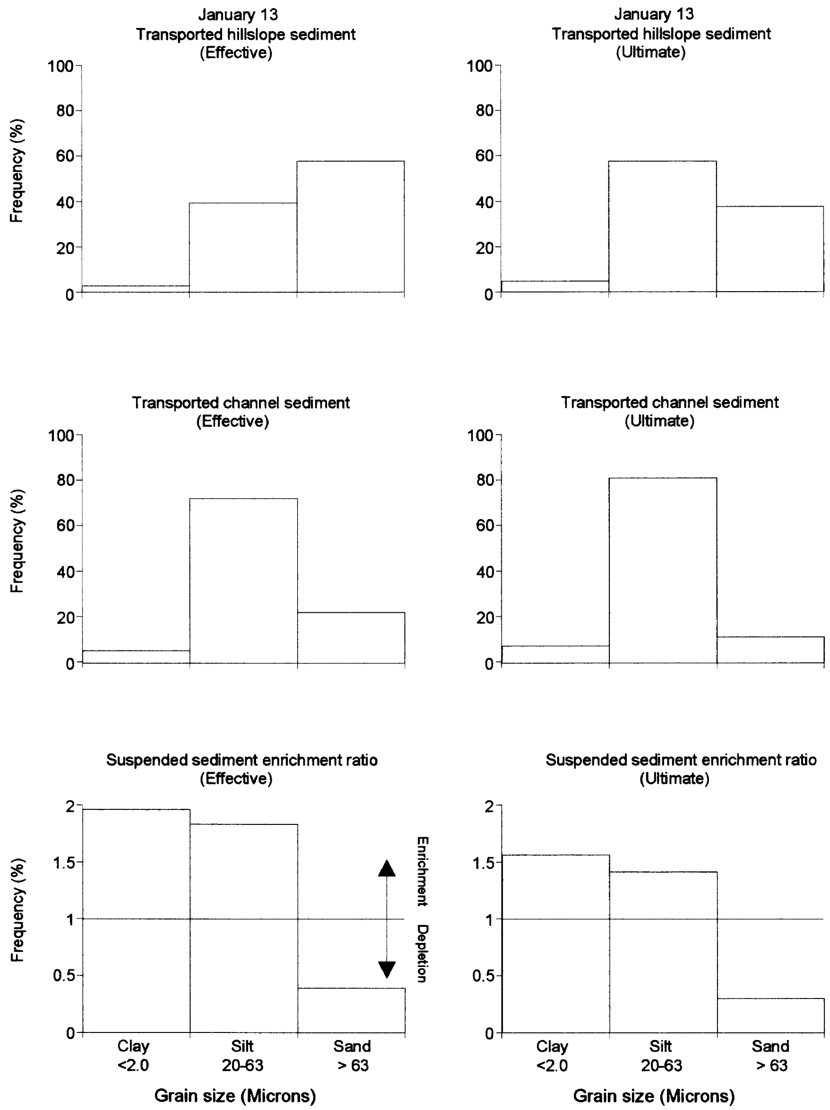

Figure 7. Comparison of mean effective and ultimate particle size distributions of transported hillslope sediment and stream suspended sediment for the 13 January 1993 storm. The enrichment/depletion ratios were calculated using Equation 2.

SUMMARY AND CONCLUSIONS

This paper has provided detailed information on the particle size characteristics of hillslope sediment and fluvial suspended sediment in the form in which it is eroded in the field under natural rainfall. The major findings from the sediment size analysis may be summarized as follows.

1. The size distribution of the eroded (undispersed) sediment was coarser than the size distribution of the sediment's primary particles, both in the stream sediment samples and the surface runoff samples, because much of the sediment was in the form of aggregates.
2. The relationship between the particle size characteristics of stream suspended sediment and discharge was complex. Generally, the proportion of fines (i.e. silt and clay) increased and the proportion of sand-sized sediment decreased with increasing discharge. This pattern, which is contrary to the traditional

assumption of a positive discharge/particle size relationship, is thought to reflect: (i) the influx of silt and clay, predominantly the former, originating on the catchment slopes and brought to the stream by overland flow along vehicle wheelings, roads and tracks; and (ii) entrainment of fine material from the bed and banks of the channel. Thus, the study suggests how important (and neglected) the removal of channel-bed deposits is, particularly during the rising limb of the hydrograph. During large storms, however, the proportion of sand-sized sediment increased during the rising limb of the hydrograph, as a result of the entrainment of coarser source material from the valley floor during overbank flooding.

3. Inter-storm contrasts in particle size characteristics were evident, with suspended sediment becoming finer and less well aggregated with time following slope cultivation in the early autumn. Stream suspended sediment became noticeably coarser following an extended period of ground frost; disruption of the soil surface by needle-ice activity appeared to 'reset' the system, making coarser sediment more readily available for entrainment and subsequent transport.
4. The size distribution of the undispersed eroded material in surface runoff was related to flow conditions: flows with large discharges and velocities (i.e. rills) transported a larger percentage of coarser aggregates than less erosive flows.
5. Sediment leaving the catchment contained considerably more fine particles than that present in the matrix soil or that eroding from the catchment slopes. This was due to (i) the selective erosion and delivery of fines to the stream channel by runoff adjacent to the stream, and (ii) the preferential deposition of the coarser fraction during sediment delivery, in the present case, in depositional fans along field boundaries and along the valley floor.
6. Preliminary data indicate that most of the aggregation evident in the stream sediment reflected the persistence of primary, soil-derived aggregates.

In conclusion, two key points emerge from this study. First, it is clear that the particle size characteristics of fluvial suspended sediment are controlled not only by the hydraulic conditions within the channel itself, but also

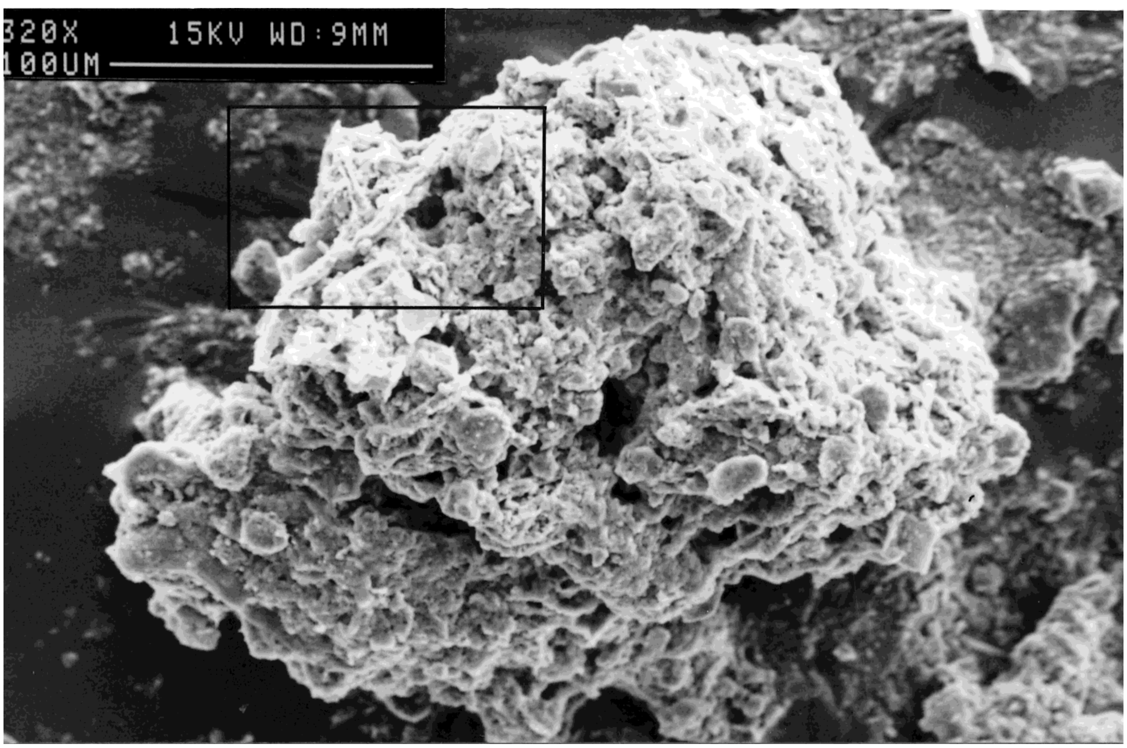

Figure 8. Scanning electron micrograph (magnification 320×) of channel sand-sized aggregate sampled during the 9 April 1993 storm. Note organic matter and root hole within highlighted area

by the erosion and sediment delivery processes operating throughout the basin. Second, any attempt to elucidate the sediment delivery dynamics of a drainage basin must take account of the potential contrast between the ultimate and effective particle size distribution of the sediment in response to aggregation. This paper has confirmed that a significant mode of sediment transport in fluvial systems is in the form of aggregates. Thus, large errors may result if the transportability of sediment is inferred from dispersed size distributions rather than the actual or effective sediment sizes.

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